Fundamentals of
MICROFABRICATION

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Integrated Power

As in the case of portable computers, small, light-weight and long lasting energy sources are one of the most urgently needed breakthrough technologies. Microsystems require even smaller power sources, as weight and volume of on-board energy sources are disproportionately large compared to the microsystems they power. The roles of energy storage and energy dissipation in microsystems differ considerably from the world of practical daily experience. Designing microsystems demands close examination of energy budgets and taking advantage of the merits of smallness as well as minimizing its adverse effects.[127]

The specific energy (energy per volume unit) of the power source determines the proper active volume for a given application. If the volume of the packaging is taken into account, energy volume densities of lithium batteries may reach 240 to 360 Wh/l. These lithium-based batteries generate the highest specific energy of any commercially available battery. In these batteries the anode, consisting of high purity lithium, may be combined with many different cathode materials, resulting in different voltages ranging from 1.5 to 3.9 V. Organic solvents in which lithium salts are dissolved and conducting solid polymers function as electrolytes. Beyond button Li batteries 4.8 mm (dia.) by 1.4 mm (high) used in watches and cameras, progress in miniaturizing high-energy density power sources has been limited. Button Li cells are now the best available energy sources for microsystems. Batteries and fuel cell materials deposited with IC technologies on the device substrate itself are in the research stage.[128] Often the thin film materials deposited in constructing those batteries, such as Li, TiS_2, V_2O_5, etc. prove incompatible with the IC process, and the prospect of integrating them with ICs seems remote. Ultrathin, solid state Li cells, 'energy paper', also start to emerge. Kanebo introduced the polymeric PAS (poly-acenic semiconductor)-based battery in 1993. The polymer PAS film in the battery is only 200 μm thick and has an active surface area of 2200 m^2/g. It serves as the anode and the cathode is again lithium based. The voltage is 3.3 V, corresponding to 3 Ni-Cd elements in series. Unfortunately, the energy density, taking the complete, packaged battery into account, is only 5.5 Wh/L.[127] The reversibility, absence of polarity, and extended lifetime of supercapacitors make them an attractive alternative for power in microsystems. Supercapacitors with energy densities of 1.9 Wh/L and slightly higher are available. In supercapacitors an electrical double layer on a very high surface area material such as activated carbon or IrO_x is reversibly charged and discharged. Since it is possible to carbonize photoresist materials, make them porous, and charge them, it seems feasible that ultracapacitors could be integrated on ICs. The overwhelming issue to overcome, just as in the case of a chemical sensor, is packaging. Supercapacitors and batteries incorporate very corrosive and reactive materials, making the challenge even more daunting. All of the above tend to suggest a hybrid implementation as the only possible means of integrating supercapacitors or thin-film batteries with ICs.

Power generation by the alternate heating and cooling of a working fluid or a solid (e.g., shape memory alloys) integrated on a chip has been attempted for driving a load. The heating in such an engine results from passing a current through a resistor. It would be preferable though to use infrared radiation instead, since no leads need to connect to the chip. It has been projected that a gas-based heat engine of $5 \times 5 \times 5$ mm^3 might provide an output of 10 to 100 W/kg. With actuators based on shape memory alloys, an output of up to 1 kW/kg is feasible, with an efficiency ten times lower.[127] Several problems are associated with crafting MEMS engines, including the thermal isolation of heating and cooling sections, minimization of friction, and the difficulty of implementing a flywheel. Some of these problems were successfully addressed by Sniegowski et al.[129,130] who demonstrated a surface micromachined microengine capable of delivering torque to a micromechanism. Angular velocities of 600,000 rpm were registered for the engine driven by an electrostatically comb drive. In an alternative construct, the same engine was also driven by steam.

Given the size of power sources, generating electricity on board or supplying energy from the outside often is preferred. One interesting way to accomplish this, used for several decades in wristwatches, is to use a microgenerator. An eccentrically rotating mass driven by wrist movements supplies energy to a spring. A mechanical watch requires 1 to 2 μW. In order to keep the watch working for 48 hours after it has been removed from the wrist, the loaded spring must contain 4.8 10^{-5} Wh. Given the size of the microgenerator, the system stores about 0.3 Wh/L, more than two orders of magnitude smaller than the specific energy of a button cell for quartz watches. In an automatic quartz watch, the microgenerator drives an electric generator, the electrical energy is then stored in a supercapacitor powering the quartz oscillator, IC, and stepping motor of the watch. The power requirement of a high-quality analog watch is as low as 0.5 μW.[127] As Goemans points out, the possibility of converting motion into electrical energy can be very attractive for cases where battery replacement is unacceptable, kinetic energy is abundantly available, and space is not too limited. He lists biomedical implants, tire pressure monitoring systems, and electronic locks as potential application areas.[127]

Thermo-electric converters may extract energy in applications where heat and temperature difference are available 'for free'. Thin-film thermocouples have been used to power a watch based on the temperature difference between the cool front face of the watch and the warm skin contact. A disadvantage of this approach is the very low efficiency of the conversion.

We already discussed the implementation of a high-voltage, integrated solar cell array by Lee et al.[131] as an electrostatic MEMS power supply (see Chapter 5). The conversion efficiency in that effort was only 0.2% though. Sakakibara et al.[132] were able to generate more than 200 V with a similar solar cell on an area of 1 cm^2 and obtained a conversion efficiency of 4.65%. In both cases amorphous silicon was used in a triple-stacked photovoltaic structure generating up to 2.3 V per cell. To obtain a very dense packing of array elements and to make the series connection of the solar cells, the latter group used focused laser beams for patterning electrodes and photovoltaic materials. For future thin-film photovoltaic cells, efficiencies of over 30% are expected. Solar cell technology represents the most MEMS-compatible

technology for power integration. Since solar light is only intermittently available, electric storage elements need be implemented as well. Along this line Kimura et al.[33] fabricated a miniature opto-electric transformer consisting of a p-n junction photocell and a multilayer spiral coil transformer. Besides photovoltaic converters for solar light and laser light, microwaves could be used to power microsystems. In the latter case, extremely small receivers and converters would need to be built.

For URLs on scaling, actuators, and power sources, see Appendix B.

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